Hybrid Renewable Energy Co-generation – A Comparative Study

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***Abstract*— Globally there is a lot of academic interest in cleaning up the process of power generation. In the Kurdistan region to the north of Iraq there is a high potential for renewable energy power generation. Solar insolation reaches an annual average of 5.27 kWhr/m2/day. Wind energy is plentiful and wind speed can achieve an annual average of up to 7 m/s at a height of 100 m from the ground. Also there are over 60 proposed locations that have been marked for dam locations in Erbil, one of the three northern provinces of the country alone. There is a large need for additional power (from 25 to 45%) and combining all available resources in a hybrid network for power generation can substantially reduce the need for grid connection.**

This paper investigates the simulation of two micro hybrid systems, for up to 3 kW of electric power generation, using hybrid optimization model for electric renewables, known as HOMER. One located in a metropolitan area, to compensate for interrupted power supply and appointed as deferrable load in the simulation, combining the merits of solar panels with a backup diesel generator. The other located in an off grid area, supplied by micro-hydro generation, solar PV system, a wind turbine and a standby diesel generator.

A cost of 1.4 $/Watt is the minimum estimated amount for the PV system and the optimum angle for around-the-year performance was established to be; facing south at 36º inclination angle from horizontal. The standalone scenario at remote area achieved better sustainability results, where the load was shared up to 19% by PV system, wind energy produced up to 51%, micro hydro-turbine about 28% and the diesel generator was needed for only 2% of the demand. The metropolitan system divided the load during the interrupted power by 52% for PV system and 48% for the diesel generator. The resourcefulness of the remote area case led to the reduction of diesel generator emissions by (13) times.

Keywords-component; micro hybrid, HOMER, energy, standalone

I. INTRODUCTION

One of the main sources of renewable energy is solar energy. It is found in abundance in the region, as the average annual insolation incident on a horizontal surface reaches 4.86 (kWhr/m^2/day) with the possibility of averaging 5.26 (kWhr/m^2/day) at a tilt angle of 36º, for equator-pointed tilted surface [1]. The tilt angle is selected based on comparison of data from horizontal panel with that from 21, 36, 51 and 90 degrees, as shown in figure (1).

In recent years a large amount of photovoltaic (PV) systems have been installed worldwide due to the environmental transformation from fossil fuel to clean sustainable energy. The growth in installed solar capacity has soared to 15% in United States and other countries like, Germany, Japan, India and China are showing similar plans for increasing power production from renewable energy [2].

Another source of renewable energy is wind. Figure (2) shows monthly averaged wind speed for 36 latitude by 44 longitude, at different heights from the ground [1]. The indication is that at heights of 50 meters and higher, the annual average wind speed exceeds 6 m/s which is rated as fair to good and transposes as suitable for wind turbine power generation [3]. Standalone wind turbine power plants can be integrated into hybrid power systems, including photovoltaic and photovoltaic and diesel generator [4].

Hydropower is a source for sustainable clean power generation. Run-of-river type of hydropower generation unit uses the running water directly to power a turbine. Here the power generation is dependant on the instantaneous state of the water source [5] and it is restricted to periods of abunance in water flow. In suitable remote areas where the possibility of installing micro-hydropower turbines exists, it can be a source of power generation with seasonal reliability. In Erbil governorate where the regional water resources administration has estimated the possibility for up to 60 dam locations (Directorate of Water Resources, 2010), there is reasonable potential for seasonal hydropower generation in many off-grid areas.

A. Hybrid power generation

A hybrid power generation system is an autonomous system capable of assembling renewable energy sources into a conventional generation system such as a diesel generator [4]. The system may combine, “PV and wind”, “PV, hydro and diesel”, “wind, PV and diesel”, etc. Supply of sufficient power quality is the main purpose of such systems, keeping in mind the maximum envolvement of renewable resources in the power generation process. The balance for instaling such systems is struck between low or no cost of fuel and cheap running costs compared to the high investments required for renewable power generation system installation.

Hybrid systems reduce the fuel and operation and maintenance costs on supportive conventional systems, such as diesel genertor. There is also the possibility for increasing the output based on variation of sources when the demand is increased, and the thermal and chemical pollutants are proportionaly reduced [6].

B. Hybrid system simulation software

- There are a number of hybrid simulation optimization tools available [7] and [8], like; HYBRIDS, RETScreen, iHOGA, INSELL, TRANSYS, ARES and HOMER.

"HYBRIDS" is capable of singular configuration simulation. The analysis is based on average monthly wind and solar data and daily average load with the disadvantage of not being able to optimize the configuration. It is developed by Solaris Homes.

"RETScreen" is a Canadian viability-oriented code for estimating environmental and economic impacts of combining the output of a number of renewable energy technologies at any specific location around the globe. Technical evaluation is based on the amount of load and its balance against the produced energy [9]. The programing is based on visual basic and "C" language and the weaknesses lie in exclusion of temperature effect, lack of data integration, weaknesses in; modeling and calculation ingenuity.

"HOGA" stands for hybrid optimization generic algorithm. It is based on C++ platform developed for sizing hybrid energy generation systems in Spain. It is capable of adjusting panel inclination and performing probability and lifecycle emission analysis. The optimization is carried out using one-hour intervals and the control strategies are improved with generic algorithms [10].

"INSELL" is integrated-simulation-environment-language based on graphical modeling. It was developed in Germany and is oriented towards a frame based on its own library with climatological data from around 2000 sites. The software is similar to TRANSYS and includes a graphical interface meaning that models can be developed without the need for familiarity with programing [11].

"TRANSYS" is developed by joint work between Wisconsin and Colorado Universities. It is based on modeling using FORTRAN mainframe and is considered a flexible tool for transient system simulation. It has a number of simulation frames for calculation of solar energy on sloped surfaces [12]. However, the software is not able to produce optimization schemes.

"ARES" is autonomous-renewable-energy-system. It is developed in Wales by Cardiff University for renewable energy analysis. It is based on using metrological data and input load to estimate the probability of system autonomy. The software has two versions, the basic "ARES I" and "ARES II", which is modified to include the renewable energy sources as subroutines [13].

"HOMER" is based on hourly assessment of the needed energy to counter the load requirements. The hourly span incorporates the whole period of evaluation considered for the system based on twenty-four hours a day and estimating for the whole number of years selected for evaluation [14]. The calculation flow chart is adjusted to find the minimum charge combination based on the selected options, as component layout, for the trialed electrical systems. HOMER configures the final cost after going thought a large number of simulations and then produces the outcome of responsiveness evaluations for the considered arrangements.

Figure (5) shows a comparison for the above mentioned software in terms of the number of options; technical analysis (TA), economic analysis (EA), photo voltaic panel system (PV), wind turbine (W), diesel generator (G), storage device (ST), bio-energy (BIO), hydropower (HYD) and thermal system (T). As shown in the figure HOMER stands out amongst the other software and that is the reason for its popularity in the academic scene. The merits of this software are ample as in addition to using anisotropic model for solar photovoltaic system, it has a very strong database engagement diaspora [8] that includes, a variety of:

- Technical options
- Component costs
- Resources
- Manufacturers data

All of the above are complemented by the fact that this software's strength is in sizing and optimization with a strong user interface that abridge accurate analysis of the system [15].

C. Problem statement

- Insufficient power supply is a day to day and rising issue for many of the developing countries. The normal growth of the electrical grid and the corresponding conventional power generation schemes are simply no match for the demand. The local regional sector is a good example of such a case as according to Ministry of Electricity, the demand for electricity in Erbil governorate, has been growing by 18 to 30% from 2011 to 2014 [16]. This has made power interruptions, in peak demand seasons, summer and winter, very frequent (6–8 hours) and diesel generators have been deployed to partially share the load.

- Also distant places form a challenge when it comes to supply of electric power. Diesel geneator is commonly used in remote villages in the region. The advantages include low investment cost and minimal operation and maintenance needs while the disadvantages of extensive operation hours are many and include, fuel delivery cost, pollution and noise amongst others. To improe the situation, the natural resources, such as wind, solar and seasonal hydro, in that remote location may be used to form a hybrid power systems to provide support for a stand alone diesel generator. And since increasing the options based on renewable energy sources, leads to more dependability and, in energy terms, relative reduction in costs, then hybrid systems are more reiable and less demanding than considering only a single renewable energy source [17]. However a number of factors must be taken into consideration when choosing off-grid hybrid systems. The most important of which are the budget and dependability.

- For the two cases mentioned above namely, interrupted grid supply, when the utility power is off for a number of hours and the case of a remote off-grid location with limited power requirement, for both of which the diesel generator has been the only alternative, we have attempted to simulate two separate micro hybrid systems in this paper. The common points between the two system are:

- Limited power generation (3kW)
- Solar photovoltaic panels
- Diesel generator support
- Inveters
- Supply management system

Case I: Interrupted grid supply
Figure (3) shows a hybrid system based on solar photovoltaic (PV) panels and a diesel generator. This system has the ability to provide the required power supply for the period in which the grid is off. There are environmental, resources and logistical issues that benefit from such a system. The shortcoming is the installation cost that needs to be addressed and evaluated against the benefits. The reliability of such a system depends on coordination between the two subsystems, the time of the day, seasonal factors, availability of diesel fuel and maintenance of the diesel generator.

Case II: Remote off-grid location
Figure (4) shows a hybrid system based on solar, wind, seasonal hydro and diesel generator. The main advantage of such a system is being able to use natural resources and reducing the need for diesel fuel and also reducing generator operation and maintenance costs. The capacity of using three renewable sources gives extra generation and reliability credit to the system. Again the main disadvantage of such a system is the capital cost.

II. Theoretical Analysis

A. Solar energy

The availability of solar energy is restricted to daytime hours and the monthly average daylight hours for this region is estimated at (12.084) hours [1]. There are a number of parameters that dominate the output of a panel, including; incident solar radiation on the array ($G_{tot.}$: W/m^2), panel efficiency (η_p) and panel area (A_p) [18]:

$$P = G_{tot.}\, A_p\, \eta_p \qquad (1)$$

Panel efficiency (η_p) is an important factor in panel power generation and it depends on; power modulation based on maximum power point tracking efficiency (η_{mpp}) and the efficiency of any power tracking equipment (η_e) leading to:

$$P = A_p G_{tot}.\eta_{mpp,ref}\eta_e[1 + \frac{\eta_{mpp}}{\eta_{mpp,ref}}(T_a - T_{ref}.) + \frac{\eta_{mpp} G_{tot}.}{\eta_{mp,ref}}\frac{\tau\alpha}{U_L}(1 - \eta_{mpp.ref}) \qquad (2)$$

B. Wind energy

The fluctuation of wind energy is exceeding all other sources of renewable energy. The prediction of wind patterns and their intensity based on average annual projections requires intensive data collection at different locations and over extended periods of time. Wind energy prediction is a science of many variables and power software like; European Standard; WAsP (wind atlas analysis and applications program), NOABL (numerical objective analysis of boundary layer) and ETSU (energy technology support unit) are mostly based on MCP (measure, correlate and predict) technique, all suffer from measures of unreliability but still have become a basic part of feasibility study for the location of wind tower installation [19]. The power extracted from the wind is based on the rotor area (A), air density (ρ), the cubic upstream velocity (V), the mechanical efficiency of the rotor (η_m) and the power coefficient factor (C_p) [20]:

$$P = \tfrac{1}{2}\, C_p\, \eta_m\, V^3 \qquad (3)$$

And C_p represents a fraction of upstream wind power captured by the rotor blades and can be determined based on the upstream and downstream velocities [21]:

$$C_p = \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2} \qquad (4)$$

The value of C_p ranges from 0.2 to 0.4 for slow multi-blade turbines to 0.59 at maximum theoretical value. The relation between velocities with respect to the effect of height and topography is note worthy and is represented based on the height (Z) by [22]:

$$V_z \ln\left(\frac{Z_r}{Z_o}\right) = V(Z_r) \ln\left(\frac{Z}{Z_o}\right) \qquad (5)$$

C. Hydraulic turines

The case considered is for small hydropower generation plant. There is no water storage and power is produced only when water level is high enough for the turbine to run at rated speed. The considered water heads are minimal and seasonal variations are considerably large [5]. There are many types of turbines, such as axial, vertical cross flow, venturi and gravitational but hydrokinetic turbines (also known as; low pressure run of the river ultra low head turbines), an affiliate of cross-flow family is most suited for this application, with capability of operation under 0.2 m of head [23]. The generated power is based on combining continuity and energy equations and can be expressed in terms of the cubic flow velocity (V), [24]:

$$P = \frac{1}{2}\rho C_k A V_{wat}{}^3 \qquad (6)$$

D. Diesel generator

A diesel generator's efficiency in power generation is restricted by the diesel engine that runs it. Thermodynamically Carnot cycle indicates the upper limit of the performance of any heat engine, including the compression ignition engine, also known as the diesel engine, [25]:

$$\eta_{Carnot} = \frac{T_H - T_L}{T_H} \qquad (7)$$

However, the overall efficiency is a function of a number of engine characteristics, such as compression ratio and cutoff ratio, working against the generation unit efficiency, [26]:

$$\eta_{overall} = 1 - \left(\frac{1}{r_c}\right)^{k-1} \left[\frac{\beta^k - 1}{\{k(\beta - 1)\}}\right] \cdot \eta_{generator} \quad (8)$$

In energy generation the most efficient mid size diesel generators' overall efficiency is limited to 40 – 45%. The overall output power of the diesel generator is expressed in terms of:

$$P_{DG} = \eta_{overall}(2\pi\, T\, N) \quad (9)$$

E. Modeling with HOMER

Hourly energy production calculations to estimate the most feasible combination of components to meet a fixed or variable load demand based on system, life cycle and responsiveness analysis is used by HOMER to decide on the flexibility of technology, size and environmental involvement.

1) Load status and selection

Normally, the variation of load is a vital factor in estimating the ability of the selected hybrid power generation system to provide the necessary energy. However due to the particulars of local socio economic characteristics and based on a well established assumption that the generated power is distributed to the consumers according to a limited access policy that allows a preset amount of power to each consumer, it is assumed that the hybrid system needs to provide a limited output to the micro network. This output is defined below for two such systems.

This assumption holds for both cases of; "compensating interrupted power" in the metropolitan area and the "off-grid" remote area scenarios, considered in this work. The load requirement considered for each of these cases may reach up to 3000 Watts. This amount is selected to fit the following criteria:

- An average residential unit power requirements, estimated at (3000 W).
- Participation of renewable energy up to (3000 W)
- Allocated amount of capital for retail and assembly for solar and diesel systems is $ 6000. The additional cost for wind and micro hydro turbines is not included in this allocation, as they are not considered for the metropolitan application. This is broken into:
    - 12 panels at $250/panel totaling at $3000
    - Invertor, charge controller and maximum power point tracker, assembled in one unit, cost estimated at $800
    - Two storage batteries, estimated at $200 each totaling $400
    - Diesel generator estimated at $800

Remaining $1000 left for wiring (assuming the system is assembled in a near by area), installation and unforeseen or unaccounted for expenditure

2) The approach to the simulation process

It is consisting of a case where the grid fails. The assumptions are based on:

Case I: Compensating interrupted power - metropolitan

a) Description of load requirement:

It is assumed, based on the actual local reality, that the power source from the grid is suffering from the inability to meet the daily demand. The considered case is built around the following conditions:

- The failure period is assumed to last for up to eight hours during 24 hours.
- It is assumed that 40% of the failure occurs during the daytime hours (availability of sun light) and the rest (60%) during the night.

b) Hybrid system description:

The compensating power considered is a hybrid system made up of:

- Diesel generator (5 kVA) diesel generator, supported by;
- Photovoltaic system of (3 kW) made up of:
    - Photovoltaic panels (12 panels); nominal power 200 - 250 W (+/- 5%)
    - Two battery packs 100 A.hr
    - Inverter (3000 W – pure sine wave)
    - Connecting wiring and apparatus

c) Simulation tool is HOMER

Case II: Off-grid - remote area model

If there is sufficient amount of electricity generation for a specific expansion, connecting a remote location to the grid is a matter of demand, planning and availability of revenue for grid expansion. In power transmission terms, despite the fact that overhead line technology is considered the cheapest when compared to other available technologies like underground cable, the lifetime cost assessments are in the range of 2.2 to 4.2 million Sterling Pounds (3.3 to 6.3 million dollars) per kilometer [27]

Comparing the possible means for delivering electricity is highly affected by the required costs. Diesel generators are an established and rapidly installed technology that is usually considered for back up power when the location is already connected to the grid. The costs related to connection to grid are based on the remoteness while renewable energy sources are configured by the size [28]. Based on the details mentioned above this case is considered for a stand-alone power supply, comprising of a diesel generator and renewable energy support. Hydropower availability was a prime factor in deciding on a location to model. The selected position had to be close to a suggested hydropower source that can provide resources for micro-hydro power generation. The selected spot is at (36°57'55.44" N 43°74'96.84"E), location proposed by the regional Ministry of Natural Resources for future construction of micro-dam [29]. It is approximately 101 km from the city of Erbil. The load to be satisfied is assumed to be controlled thought a breaker limited to a maximum of 12 Amp.

Working off-grid, the available renewable energy sources; solar and wind data shown in table 2, [1] and the micro hydro turbine based on the anticipated regional flow of hydropower form the backbone of base energy support. In this case the base power comes from a 5-kVA-diesel generator. This combination of sources is to be modeled in a hybrid connected formation.

The aim is to check the ability of the considered renewable sources in supporting the diesel generator based on their contribution to independent power generation and also in reducing the fuel consumption, pollutant flow and operation and maintenance costs of the generator. The cost analysis should reveal the requirement of each system and weather the additional costs for a more durable system are justified. The solar and wind data for the location of proposed hydropower source, latitude 36.57, longitude 43.74, are shown in tables (1) and (2), respectively. The hybrid system selected for simulation by HOMER is made up of all renewable energy sources available at the location connected with the diesel generator.

III. RESULTS AND DISCUSSION

A. Case I – compensating interrupted grid power

The simulation of this case by HOMER for a hybrid system, composing of a photovoltaic (PV) array configuration supported by diesel generator with preset load and generator hours of operation and no grid support, has investigated the following areas:

1) Electrical output

Monthly average electricity production by the hybrid system is shown in figure (6). The distinction between day and night in terms of generation requirements as 40% for the day and 60% for the night has set a predictable pattern. Demand defines the production rate and the minimum is noted for the month of April when cooling and heating loads are minimal. The maximum production rate is required for the months of December and January when the heating load is at its peak. It is shown that the highest generator contribution and with it the maximum fuel consumption also occur during these two months. Except for the months of April and May, the variation in generator contribution is minimal as the size of energy storage is not sufficient for active load sharing during the night.

2) Generator load configuration

Figure (7.a) shows the diesel generator generation duty. The task is based on eight hours of power generation by the diesel generator, with the distinction that during the first four and half hours, the hybrid system optimizes the power sharing between the PV system and the diesel generator while for the remaining three and half hours, the diesel generator is forced to operate to provide reliability for the generation system. The scheduling is designed to provide generator support during the most sensitive and peaking load demand. During the load sharing time the PV system generation and storage play a major role in reducing the need for the generator while during forced operation the load dictates the generator fuel consumption. Figure (7.b) shows the variation of generator output with respect to time of the year. The color-coding shows the load-sharing pattern growth and distribution. It is highlighting the interaction of the two systems during the earlier hours of darkness and also the intensity and on the other hand, the intensity of generation based on timing related to load.

3) Photovoltaic output

Figure (8.a) shows the output of the PV system during the year. It is showing the performance of a system whose panels are fixed and installed at a slope angle of 36º, for optimal around the year performance, based on an angle estimation from a quadratic regression equation [30], facing south (azimuth angle = 0º). To validate the slope angle selection for optimum annual PV output, HOMER was run for a set of different angles, as shown in figure (8.b). The selected angle of 36º provided the highest output at 3327 kWhr/year. Figure (8.a) is based on color intensity and it shows better performance during August through April. This setting optimizes collection during the winter months and partially neutralizes the exposure during the peak of summer temperature rise to minimize the implications of panel exposure to extreme temperatures. The variation of ambient and corresponding panel surface temperature is shown in figure (8.c)

4) Generator contribution

Figure (9) shows the hybrid platform composed of the generator and the solar PV system. The figure shows the profile of power generation by the PV systems and how the remaining demand is met by the generator. While the PV system fails to fulfill the demand by up to 50%, during certain month of the year, the load sharing process makes it possible to maintain the supply of power. The slope of the PV panels is responsible for the performance of the system based on using the optimum tilt angle as indicated in figure (8.b).

5) Cash flow summary

Figure (10) shows that for the span of considered period (25 years), the most effective reoccurring factor in cost analysis of the system is the fuel. The figure also shows the significance of the other costs. The overall setting shows that the cost of retail and installation (capital cost) of the hybrid system comes in second place, followed by running and operation cost. The cost of fuel is directly proportional to the number of hours of operation and the capital cost is significantly affected by the size of the photovoltaic system. The figure confirms that even in an oil rich region, the cost of fuel is still overwhelmingly dominant, exceeding up to five times the capital cost of the hybrid system.

6) Annual cost

Figure (11) shows the projection of the required revenue for the next twenty-five years. If we consider the fuel and operation and maintenance costs to be constant over the considered time span, then the annual spending is only disturbed by the replacement costs that emerge in a time span ranging from eight years for the diesel generator to twenty years for the solar panel system. When the load is regulated by limited access through circuit breakers, the prediction of annual costs for a hybrid system becomes directly proportional to fuel cost.

B. Case II – Off-grid - remote area model

The simulation of this case by HOMER for a remote, totally off-grid hybrid system, composing of a photovoltaic (PV) array configuration supported by, wind turbine, hydropower and a diesel generator with load and hours of operation identical to

Case I, has extended the discussion highlighted the following points based on a comparative approach:

1) Additional cost:

Based on comprehensive renewable sources data shown in tables 1 and 2, for the location described earlier, figure (12) shows the estimated net present cost of the hybrid system and other projected parameters such as operation and replacement costs. In comparison to the previous metropolitan case, the capital cost has grown to include wind and hydropower but the cost of annual fuel consumption has reduced ten-fold, due to the support provided by the extensive hybrid system.

2) Supplemental power generation:

Including the additional energy generation sources in the hybrid system has thoroughly changed the load sharing amounts. Figure (13) shows the differences between the two cases in terms of their annual participation in power generation. The nighttime demand has been shared by all available sources and except for January and February; the nighttime demand is mostly met by hydro and wind power. This is a major advantage available to remote area locations with access to micro hydropower resources. The contribution of wind turbine (type: Generic) is shown in figure (14). The color-coding indicates the level of output. Based on the data in table (2), the minimum is occurring during the months of November and December. During these months the hydraulic turbine, figure (15) compensates for the required power and the renewable components of the hybrid system remain effective.

3) Emissions

Table (3) shows the expected type and amount of standard emissions from the diesel generator used in the considered cases II and I. The largest amount of emission is carbon dioxide and one of the most significant components for a diesel generator is the amount of NOx produced during combustion. When comparing the two cases, figure (16), a variation of up to thirteen-fold is observed. The obtained results strongly support the case for hybrid power generation in resourceful remote areas in terms of level of emission for all constituents indicated in table (3).

IV. CONCLUSION

Based on the work done in this comparative study, it is concluded that standalone hybrid micro-power generation in the region for both metropolitan and remote area cases, is a valid option to be considered, especially when the grid is showing increasing weakness.

The load sharing ability of a hybrid system makes it possible to reduce the generator fuel consumption and with it the pollution rate. Pre programming the demanded load helps in improving the supply plan but put some stress on the consumer. This scenario can be workable for micro power generation but has to be better tested for a more extended load.

The photovoltaic system imposes the highest capital cost and needs to be finely adjusted for its application in the metropolitan standalone setting. A cost of nearly $ 5800 or 1.4 $/Watt is the minimum estimated amount and can be secured only with optimum individual ordering and installation costs. A sun tracking system is more efficient but increases the capital and installation costs with inflated maintenance. The best option for a fixed panel system for around-the-year performance was established to be; facing south at 36° inclination angle from horizontal.

Assembly of all available renewable sources on a hybrid platform in an off-grid remote location has achieved a number of goals not attainable by the metropolitan set-up. The system was capable of sharing the load; up to 51% by the wind turbine, 28% by the hydro turbine, 19% by the PV system and only 2% was produced by the diesel generator. This compared by 52% by PV system and 48% by the diesel generator for the metropolitan case lead to the up to (13) times less emissions in remote off-grid area. This has also been transposed in terms of reduction in fuel consumption.

ACKNOWLEDGMENT

The authors would like to extend their gratitude to the Ministry of Electricity, Kurdistan Region and Directorate of Water Resources, Kurdistan Region for sharing their valuable data.

NOMENCLATURE

A: Turbine area (m^2)
A_p: Panel area (m^2)
C_k: Power coefficient
C_p: Power coefficient
$G_{tot.}$: Incident Solar radiation (W/m^2)
k: specific heat ratio
N: engine speed (r.p.s)
P: Power (Watt)
r_c: compression ratio
T: torque (N.m)
T_a: Ambient temperature (°C)
T_H: Cycle higher temperature (°K)
T_L: Cycle lower temperature (°K)
$T_{ref.}$: Reference temperature (°C)
U_L: Loss coefficient
V: Upstream wind velocity at the entrance of rotor (m/s)
V_o: Downstream wind velocity at the exit of rotor (m/s)
$V_{wat.}$: Water velocity (m/sec)
V(z): Wind speed at height (Z) (m/sec)
V_{zr}: Wind speed at reference height (z) in m/s)
Z: Height at wind speed measurement (m)
Z_o: Measure of surface roughness (0.1 – 0.25 for crop land)
Z_r: Reference height (m)

Latin:
α: Glass absorptance
η_p: Photovoltaic panel efficiency
η_{mpp}: Maximum power point efficiency
$\eta_{mpp,ref.}$: Reference maximum power point efficiency
η_e: Efficiency of any power conditioning unit
ρ: Water density (kg/m^3)
τ: Glass transmittance

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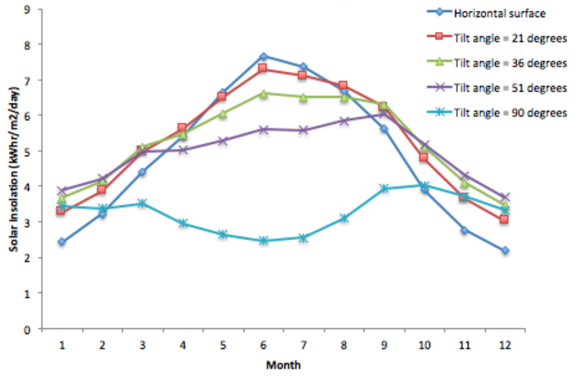

Fig. (1) Monthly average radiation incident on a tilted surface, [1].

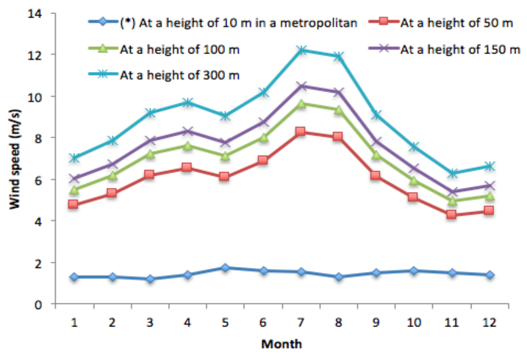

Fig. (2) Monthly average wind speed at different heights above the surface for suburban rough bare soil, except (*) [1].

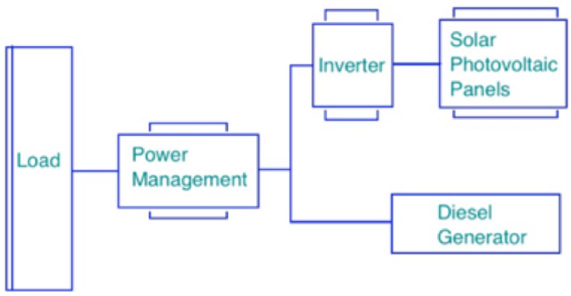

Fig. (3) Case I, solar panel and diesel generator for interrupted grid support

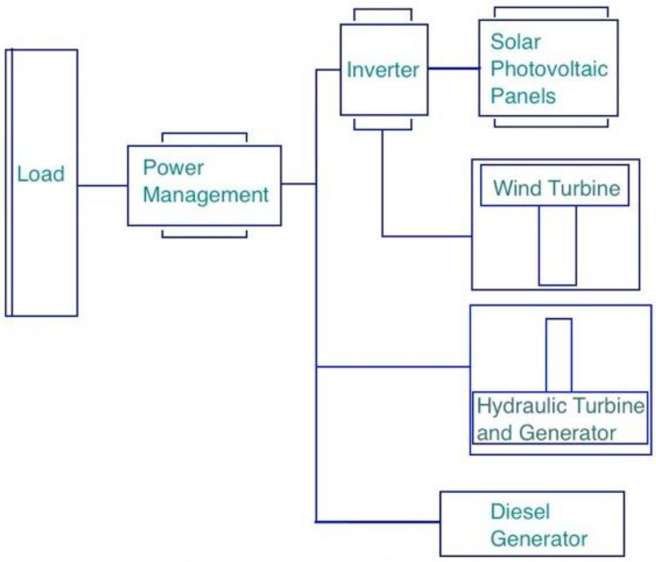

Fig. (4) Layout of case II for hybrid system in remote off-grid area.

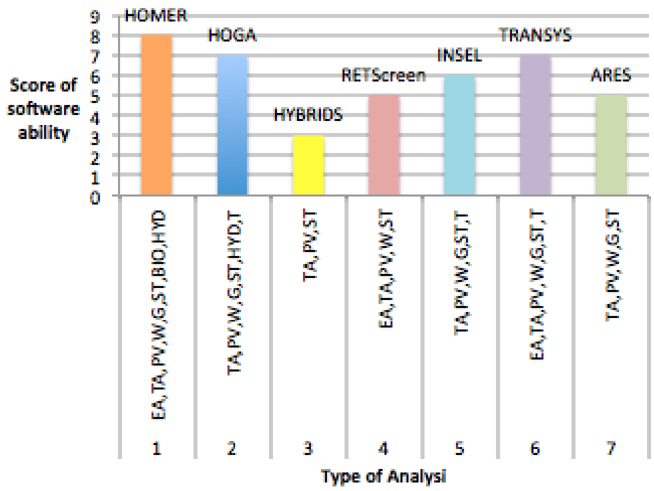

Fig. (5) Comparing capability of different software

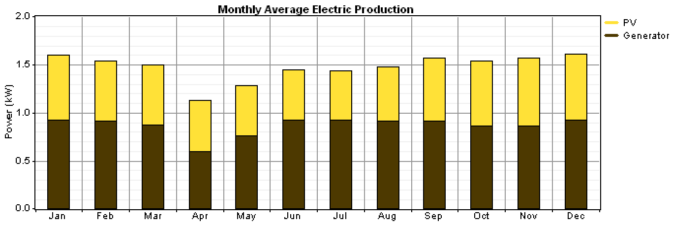

Fig. (6) showing the load sharing between the photovoltaic panels and the diesel generator

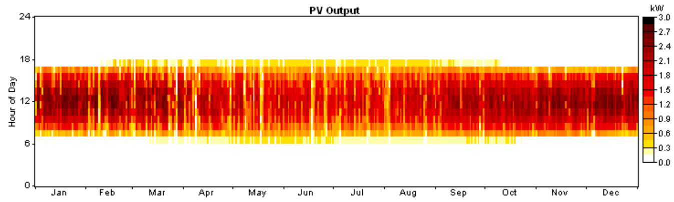

Fig. (8.a) Showing the contribution of the photovoltaic system to power generation for an array of panels facing south at an inclination angle of 36°.

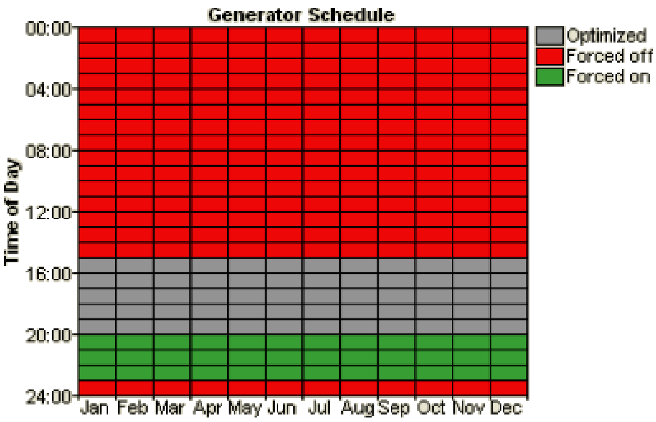

Fig. (7.a) Showing the generator schedule based on timing and type of operation for three distinctive modes of forced off, forced on and optimized.

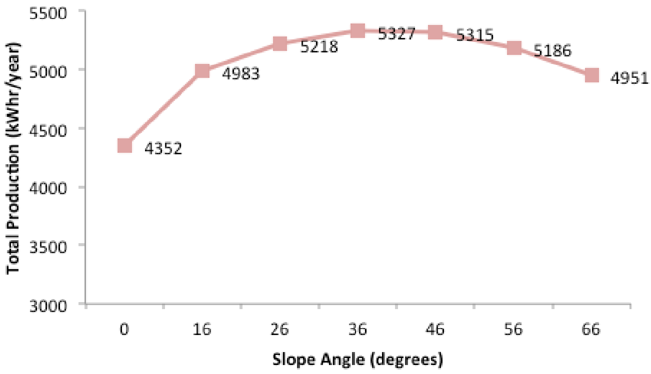

Fig. (8.b) Showing diffenent slope angles and the overall power production by PV system

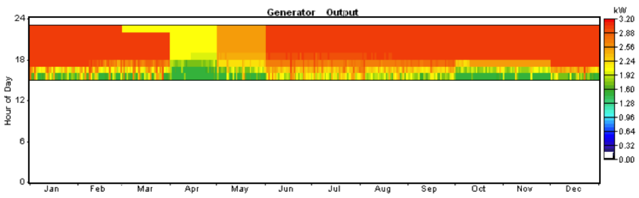

Fig. (7.b) Showing the intensity of power generation by generator with respect to time

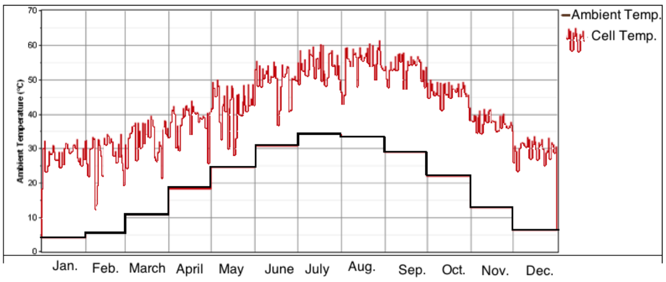

Fig. (8.c) Showing the variation of average ambient monthly temperature and the corresponding cell temperature

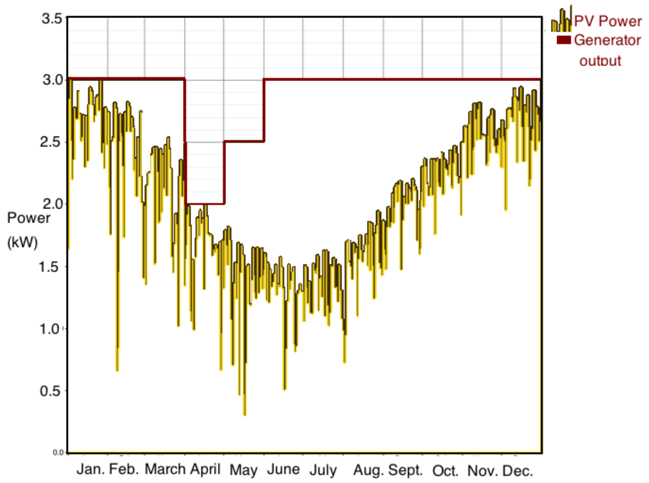

Fig. (9) Combined output of the PV system and the generator

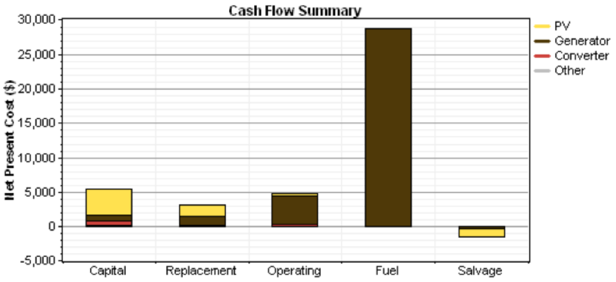

Fig. (10) Cash flow summary showing the breakdown of cost over components

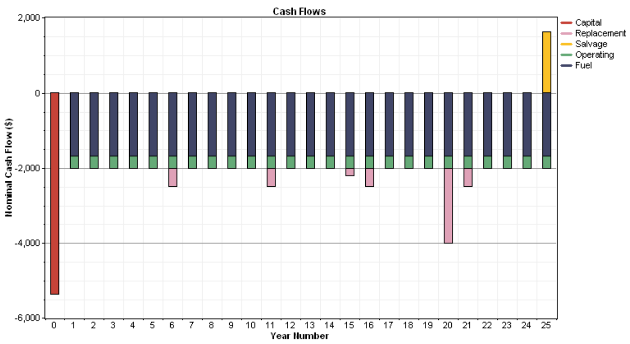

Fig. (11) Cost analysis for compensating power reflected in case I

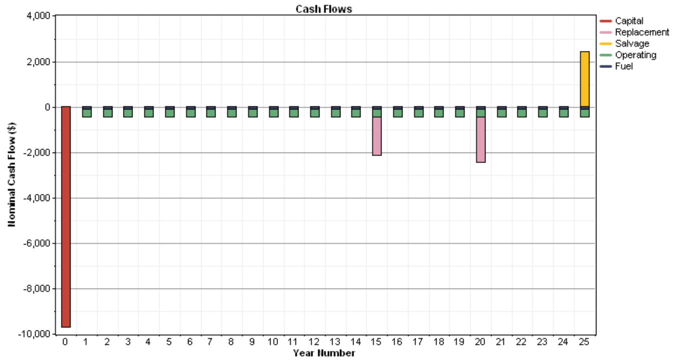

Figure (12) estimated net present cost of the hybrid system and other projected parameters

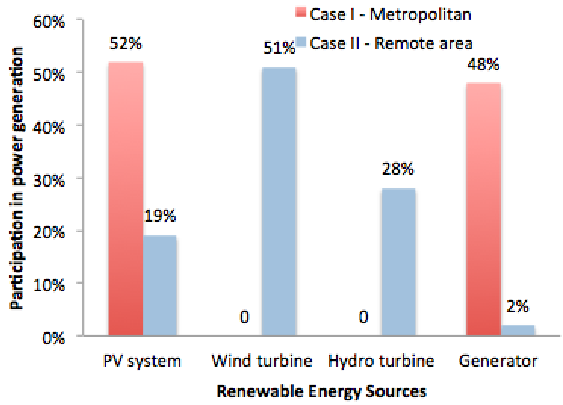

Fig. (13) Showing the contribution of the components of the hybrid system in power generation for both cases

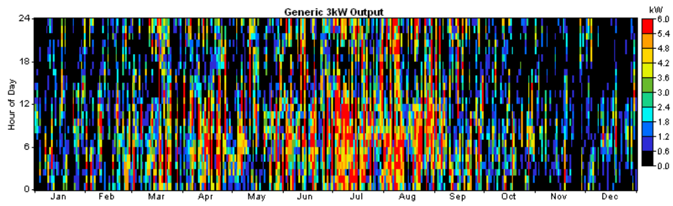

Fig. (14) Showing the contribution of (Generic) wind turbine to the hybrid system power generation

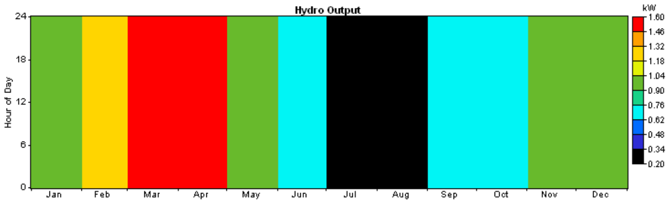

Fig. (15) Showing the contribution of hydraulic turbine to the hybrid system power generation

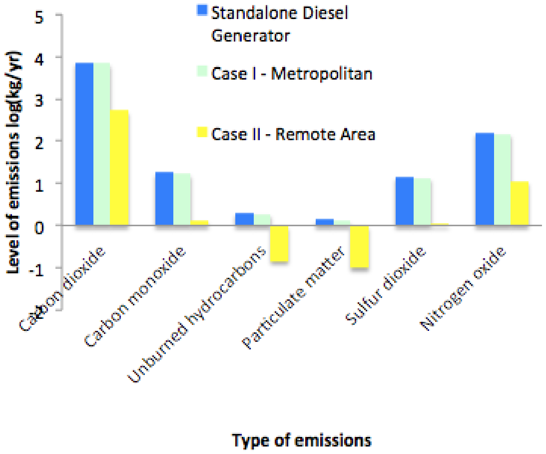

Fig. (16) Comparing the emissions of a standalone diesel generator with hybrid cases I and II

Table (1) Monthly average radiation incident on an equator pointed tilted surface (kW/m²/day) for remote location 35.57 N latitude and 43.74 longitude.

Tilt angle	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Average
0	2.66	3.61	4.80	5.69	6.66	7.88	7.54	6.86	5.70	3.74	2.75	2.36	5.03
20	3.62	4.54	5.50	5.95	6.57	7.57	7.43	7.02	6.39	4.52	3.62	3.29	5.50
35	4.12	4.96	5.69	5.79	6.12	6.86	6.73	6.71	6.49	4.83	4.05	3.79	5.51
50	4.38	5.09	5.58	5.34	5.37	5.81	5.77	6.03	6.24	4.87	4.26	4.07	5.23
90	3.87	4.09	3.90	3.08	2.62	2.45	2.55	3.13	4.02	3.77	3.65	3.67	3.40

Table (2) Monthly average wind speed (m/s) at different heights for rough bare soil for remote location 35.57 N latitude and 43.74 longitude.

Height	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Average
10	3.59	4.07	4.80	5.09	4.82	5.46	6.29	6.08	4.70	3.89	3.23	3.44	4.62
50	4.55	5.15	6.07	6.45	6.10	6.91	7.96	7.69	5.95	4.93	4.09	4.34	5.85
100	5.29	5.99	7.06	7.51	7.10	8.04	9.27	8.95	6.93	5.74	4.76	5.06	5.51
150	5.79	6.55	7.72	8.21	7.76	8.79	10.1	9.79	7.57	6.27	5.20	5.53	7.45
300	6.74	7.63	9.00	9.56	9.04	10.2	11.8	11.4	8.82	7.31	6.06	6.46	8.68

Table (3) Diesel generator emissions, as estimated by HOMER

Pollutant	Emissions (kg/yr)		
	Case I	Case II	Difference
Carbon dioxide	6841	524	6317
Carbon monoxide	16.9	1.29	15.61
Unburned hydrocarbons	1.87	0.143	1.727
Particulate matter	1.27	0.0976	1.1724
Sulfur dioxide	13.7	1.05	12.65
Nitrogen oxide	151	11.5	139.5